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Date 8 July 1957 Signed Richard E. Reedy

OFFICE SECURITY ADVISOR

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SECURITY INFORMATION

UNDERGROUND EXPLOSION TESTS

FINAL REPORT

SUPPLEMENTARY

SKEW STRUCTURES

PROGRAM

OFFICE, CHIEF OF ENGINEERS

WASHINGTON, D. C.

SECURITY INFORMATION

UNDERGROUND EXPLOSION TESTS

FINAL REPORT

SUPPLEMENTARY

SHELL STRUCTURES

PROGRAM

Copy No. 111 of 115

Office, Chief of Engineers

Washington, D. C.

June 1953

FORWORD

During the conduct of the Underground Explosion Tests at Dugway Proving Ground in the Summer of 1951 representatives of the Armed Forces Special Weapons Project proposed a supplementary investigation of skew targets (those with front faces varying from the normal incidence of 90 degrees). Such a program was to be correlated with the Corps of Engineers' buried concrete box targets in Dugway dry clay, all of which were placed at normal incidence to the direction of the explosion.

After preliminary plans were prepared and reviewed by consultants1/ to the Office, Chief of Engineers, the following program was established.

Targets - Six (6) Type "R" - Open box reinforced concrete.
Six (6) Type "T" - Closed box reinforced concrete.

Charges - Round S-2 - 2560# TNT cast blocks.
Round S-3 - 2560# TNT cast blocks.

Placement of Targets - Center of walls 6.5 feet below ground surface.
Placement of Charges - Center of gravity 7 feet below ground surface.

Instrumentation of the targets was considered to be desirable but due to the necessity for mobilizing additional instrumentation equipment and the excessive cost involved, none was accomplished. Instead, it was agreed that Professors Newmark and Norris would analyze the physical damage and correlate the damage with that observed on instrumented structures in the basic program.

The Armed Forces Special Weapons Project furnished funds in the amount of $15,000 for accomplishing the field tests. The District Engineer, Corps of Engineers, Sacramento, constructed the targets, conducted tests, supervised the damage survey and prepared the accompanying Appendix A containing pertinent data on the tests.

The analysis of the targets as reported in this report is a joint effort by the authors, Professors Newmark and Norris, acting as consultants to the Office, Chief of Engineers.

1/Profs. John B. Wilbur and Charles H. Norris, Mass. Inst. of Tech.
Prof. Nathan M. Newmark, University of Illinois

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FINAL REPORT

ANALYSIS OF SKEW TARGET TESTS

I. - GENERAL STATEMENT OF PROGRAM

In connection with the Underground Explosion Test Program conducted by the Corps of Engineers at Dugway Proving Grounds, an opportunity arose to determine the effect of varying angles of skew of the walls of underground structures on the damage to such structures produced by underground explosions. In this supplementary program, two charges were set off in the Dry Clay area at 0.2 scale (2560 pounds of TNT) with a number of underground targets of two different types, namely:

1. Open Box Targets, designated as R-targets

   These were boxes consisting only of four walls with no floor or roof slab.

2. Closed Box Targets, designated as T-targets

   These were reinforced concrete cubical boxes consisting of four walls with integrally cast floor and roof slabs and were completely enclosed except for a manhole in the roof.

The details of these targets (See Figure 3) differed slightly from the standard 0.2 scale targets used in the Dugway Underground Explosion Test Program.

The targets were set at various angles of skew and at various distances from the center line of the charge, as indicated in Figures

1 and 2, all however at very nearly the same range. Control targets set with no skew angle were included in each of the two rounds, S-2 and S-3. Altogether seven R type targets and six T type targets were tested. The complete description of the tests and a summary of all of the data obtained are contained in Appendix A entitled Supplementary Skew Structures Program, Underground Explosion Tests, prepared by the Sacramento District, Corps of Engineers and dated 1 March 1952.

II. - DISCUSSION OF AVAILABLE DATA

In general, the data available from these tests consist of survey measurements and observations of the position and state of the targets before and after the shot. No transient measurements were made of pressures, accelerations and stresses in the targets or in the soil medium. Measurements were recorded of crack patterns, crack widths, profiles of the target walls, and permanent displacements of points on the target and on the ground.

The crack patterns shown on the drawings in Appendix A can be interpreted in various ways. In this report, use was made of the maximum crack width, and of the summation of the crack widths encountered in travelling horizontally across the faces of the walls near mid-height. These measurements appeared to be somewhat more indicative of the behavior of the walls than the permanent deflections indicated by the profiles shown on the drawings.

The permanent displacements measured on the targets have not been used specifically for the interpretation of the data presented in this report although this information was used in alternate analyses which were considered. This information is recorded in Tables I and II contained herein as indication of the fact that the general nature of the displacements was reasonable, and that fairly good radial symmetry existed for each of the shots.

Calculations were made also of the change in the diagonal distances of the various targets that were placed in skew directions. These data are recorded to indicate the large deformations that occurred in the open type R-targets because of failures near the corners of these targets. Corresponding values are given also for the T-targets. However, in the latter case, these deformations were relatively small because of the restraint to such parallelogram type deformation offered by the top and bottom slabs.

Although some data are available for the behavior of similar targets in other tests in the dry clay area, it is not possible to use such data in conjunction with the present series because of variations in local conditions, the uncertainty as to the precise quantities for which comparisons could be made and the lack of data on crack width in the same form as used herein. All comparisons in the present series of tests are made among the targets which were studied in this series of two shots.

III. - PROCEDURE USED FOR STUDYING DATA

Tabulations were made of all of the available data that could be used as a measure of damage to the walls of the targets. These are summarized in Table I for the open-box type R-targets and in Table II for the closed-box type T-targets.

These tables contain the identification of the various faces in accordance with the same notation as used in Appendix A, the angle of inclination of the faces of the target to the direction of travel of the shock, and the radial distance from the center of the charge to the center line of the face considered. In the effects on the targets, the crack data is summarized including the maximum crack width near the center line of each face, and the summation of the crack widths encountered in proceeding horizontally across a face at mid-height of that face. The permanent displacements of the targets are summarized including the radial, tangential and upward movement of the nearest corner of the target, and the changes in the diagonal distances across the top of the target. The permanent deflection of each face is summarized by the maximum deflection from the chord and the maximum summation of the deflections at center line and the two adjacent quarter points at the same elevation.

It can be seen from a study of Tables I and II that the number of items of data are quite limited and that the variation in distances for any particular type of target and angle of skew is extremely small. It would be impossible to make comparisons among the various parameters from the data contained in these tables alone. Consequently it was necessary to develop a means of determining the effects of distance on the damage in order to draw comparisons of the effects of angle of skew. In order to arrive at reasonable conclusions as to the effect of angle of skew, each different angle for each type of target was considered separately and the data pertaining thereto for each of four measures of damage were plotted to indicate the type of variation with distance for the particular measure of damage considered. These plots are shown in Figures 4, 5, 6 and 7, the measure of damage being maximum crack width, summation of crack widths, maximum permanent deflection, and summation of permanent deflection, respectively.

Although the data for each individual type target are not sufficient to draw any conclusions as to the nature of the variation with distance, it is possible to use all these data to approximate a general law which appears applicable. The generalizations appear to be of the form of exponential variation with distance, with the exponent having values ranging from -4.7 to -7.9.

The data shown on Figures 4 to 7 were normalized, finally, to give the relative measures of damage for a charge 20 feet from the center of the particular face considered. Only the data for the faces nearest to the charge were used in these studies. The values obtained at a distance of 20 feet are tabulated in Table III for each of the measures of damage for the various skew angles of each of the two types of targets. A 90 degree inclination indicates that the near face of the target is normal to the direction of travel of the shock. In Table III, the data are presented as they are actually taken from Figures 4 to 7, and relative values are shown in parentheses with all values for any group related to a value of unity for the 90 degree inclination of the near face of the target.

The original values in Table III indicate that the two types of targets have slightly different resistances to the shock forces, but that these resistances were of the same order of magnitude. The relative values vary considerably and are not presented graphically because of the large variation in the different measures and because of the small amount of data available. However, one can see from the tabulated results that the most consistent data appear to be given by the summation of the crack width but that all measures of the data lead to the conclusion that for face inclinations of 90 and 60 degrees, approximately the same effects were obtained, whereas for face inclinations of 45 and 30 degrees relatively small effects were observed. This is not completely true in the case of the 45 degree inclination of the open-box R-targets. Here the damage was appreciable at this angle of inclination and became negligible at a 30 degree angle of inclination, for which angle there is no evidence in these tests that there was any appreciable damage.

It should be noted that the data used in this study were taken from the results shown in Appendix A without consideration of the fact that the deformations near the corner of the targets may have had an appreciable effect on the damage to the individual walls. It was impossible to take this into account more accurately. It was assumed that the damage near the central parts of the walls would not be materially affected, however, and this permitted the generalizations to be made regarding the angle of skew that have been developed as a result of the present study. It is noted, however, that the most serious damage in many of these targets occurred at the corners rather than at the central parts of the faces.

IV. - LIMITATIONS OF DATA AND CONCLUSIONS DRAWN THEREFROM

There are various limitations in the data that have been pointed out in the foregoing and these imply certain limitations as to the general applicability of the conclusions that can be drawn from these data. In the first place, the range in radial distances used in these tests was not great enough so that general conclusions could be drawn as to the effect of distance on the damage characteristics. Moreover, there are inherent discrepancies and inaccuracies because of the inhomogeneity of the material in the Dugway site. These are reflected in some minor inconsistencies and may have a major effect on some of the items tabulated. There is no assurance that further tests in this area would lead to precisely the same results. One should have data from additional tests (preferably adequately instrumented) for any serious further study of this problem.

Furthermore, there are variations in the physical properties of the various targets which are not represented by tests of control, specimens of either the steel or the concrete materials. These probably have only a minor influence on the problem, however.

The method used in Figures 4 to 7 to establish the effect of distance on damage appears to be the best available. This correction was also studied by an alternate approach in which the permanent displacements were used as a basis for approximating the loading applied to each target. These loadings were then used as a basis to establish the effect of distance on damage. Whereas this method led to somewhat different figures than those presented in Table III, it was encouraging to find that it also led to the same conclusions regarding the effect of skew angle on damage. The alternate method involves a number of assumptions and is not considered to be as reliable as the method presented herein.

At the beginning of the analysis of the results of these tests, initial studies indicated an approach along the following lines. Using an estimated shape for the time-pressure curve, the level of pressure on each face to give the observed deflection and degree of damage would be inferred from the results of the usual type of elasto-plastic analysis. These pressures could then be checked by a comparison with the over-all target motions. Pressure-angle relations could then be inferred from the results of this analysis. Further consideration of the test data led to the conclusion, however, that there were insufficient data to establish a correlation between the computed and observed damage. This type of analysis was therefore abandoned and it was necessary to resort to the empirical approach described herein.

V. - CONCLUSIONS AND RECOMMENDATIONS

In spite of the limitations regarding this test program, certain conclusions can be drawn from the results obtained and reported in this study. The first and probably most important conclusion is that skew targets present a much more serious problem with regard to corners and joints than do normal targets. All underground targets should be particularly well reinforced and braced so as to avoid damage to the corners in the event of underground explosions occurring at oblique angles. Roof and floor slabs firmly connected to the walls of the target appear in general to be adequate bracing but some of the damage in the T-type targets indicated that additional strengthening of the corners might have been desirable. Such additional strengthening could have been provided by fillets at the intersection of the various surfaces and particularly by special corner reinforcement. Attention should be given to the details of the reinforcement at the corners and the method of bending or hooking bars so as to provide for sufficient tensile reinforcement on the inside of the corner as well as on the outside to account for the possibility of bending in either direction depending on which diagonal is exposed to blast.

In designing underground fortifications or structures of any sort, which are subjected to underground shock, it is desirable to provide for an underground force acting against the structure in accordance with the following general rules:

(1) For walls having angles of inclination to the direction of travel of the shock between 90 degrees and 45 degrees, the design pressure should be considered to be the same as a wall having a 90 degree angle of inclination.

(2) For walls having an angle of inclination less than 45 degrees, a reduced pressure can be assumed.

(3) When the angle of inclination becomes as low as 30 degrees, the pressure is essentially the same as that for a wall which is parallel to the direction of travel of the shock wave.

More refined estimates of the effect of angle of skew might possibly be made with additional tests. However, the present test program does not warrant more accurate quantitative conclusions. In any event, most targets would be situated in such a location that normal angles of inclination on any face would be likely. Consequently, all surfaces would have to be designed for such an inclination. It therefore appears that the only additional provision that would be required to account for oblique angles of inclination is the provision of additional reinforcement at the corners.

Although the test data indicate a possibility of a slight increase in effects for angles of inclination of about 60 degrees, it is not clear from the data that this is a significant increase, or that it is necessary to consider this slight increase in design.

TABLE I - SUMMARY OF DATA FOR R-TARGETS (OPEN BOX TARGETS)

Target No.	Face No.	Angle	Radius to feet	Crack Data, inches: Max. Crack Width at ℄	Crack Data, inches: Sum of Crack Widths at ℄ Mid Ht.	Remarks	Permanent Displacements, feet: Corner Nearest Charge: Radial + out	Corner Nearest Charge: Tangent + clock.	Corner Nearest Charge: Up	Decr. in Rad. Diag.	Decr. in Tang. Diag.	Deflections from Chord, inches: Max. at ℄	Deflections from Chord, inches: Sum at ℄ and Quarter Points
				+ Cracks inside - Cracks outside									
R-4	I	90	24.0	1/8"	1/4"		+0.69	-0.04	+0.09			5/8"	1 3/8"
	III	90	29.0	3/16	5/16							- 3/4	1 1/4
	II	0	26.5	-	-							- 3/4	-2
	IV	0	26.5	-	-							- 1/2	-1 1/2
R-6	I	90	25.0	1/4	1/2		+0.54	-0.06	+0.12			1	2
	III	90	30.0	1/16	1/8							1/4	1/2
	II	0	27.5	-1/64	-1/16							- 3/4	-2 1/8
	IV	0	27.5	-1/64	-1/16							- 3/4	-2
R-1	I	90	29.0	1/32	1/16		+0.18	+0.04	-0.01			- 1/4	- 1/2
	III	90	34.0	1/16	1/16							- 5/8	- 7/8
	II	0	31.5	-	-							- 3/8	- 3/4
	IV	0	31.5	-	-							- 1/2	-1
R-7	IV	60	25.3	3/8	3/4		+0.62	+0.04	+0.16	0.31	-0.28	1 3/8	2 7/8
	II	60	29.6	1/4	3/8							3/4	1 3/8
	I	30	26.2	-	-							-1 3/8	-3
	III	30	28.9	1/16	1/8							Fracture	
R-2	I	45	26.8	-	-		+0.07	+0.08	+0.01	0.13	-0.14	- 3/8	-1
	IV	45	26.8	1/16	1/8							3/8	3/4
	II	45	30.3	1/32	1/16							1/8	0
	III	45	30.3	1/8	5/16							3/8	3/4
R-3	I	45	30.8	1/32	1/32		+0.17	0	+0.01	0.05	-0.07	- 1/4	- 5/8
	IV	45	30.8	1/32	1/32							- 1/4	- 1/2
	II	45	34.3	1/32	1/32							- 1/2	-1 3/8
	III	45	34.3	1/64	1/32							+ 1/4	+ 3/8
R-5	I	45	34.8	HL	HL		+0.14	+0.01	-0.01	0.05	-0.04	- 3/8	-1
	IV	45	34.8	HL	HL							- 1/2	-1 3/8
	II	45	38.3	HL	HL							- 3/8	-1 1/8
	III	45	38.3	HL	HL							- 3/8	-1

TABLE II - SUMMARY OF DATA FOR T-TARGETS (CLOSED BOX TARGETS)

Target No.	Face No.	Angle	Radius to feet	Crack Data, inches: Max. Crack Width at ℄	Crack Data, inches: Sum of Crack Widths at ℄ Mid Ht.	Remarks	Permanent Displacements, feet: Corner Nearest Charge: Radial + out	Corner Nearest Charge: Tangent + clock.	Corner Nearest Charge: Up	Decr. in Rad. Diag.	Decr. in Tang. Diag.	Deflections from Chord, inches: Max. at ℄	Deflections from Chord, inches: Sum at ℄ and Quarter Points
				+ Cracks inside	- Cracks outside								
T-5	I	90	18.5	1/2"	1 1/4"	Spalled on compr. face	+0.57	+0.83	+0.35		-0.03	4"	9"
	III	90	23.5	5/16	5/8							5/8"	1 1/8"
	II	0	21.0	-3/32	- 5/16							- 1/2	-1 1/4
	IV	0	21.0	-1/32	- 5/32							- 1/2	-1 3/8
T-1	I	90	20.0	5/8	1 1/2	Spalled on compr. face	+0.35	-0.27	+0.49	-0.01	-0.01	1 3/8	3
	III	90	25.0	1/16	5/16							1/8	1/4
	II	0	22.5	-1/16	- 5/16							- 1/4	- 3/4
	IV	0	22.5	-1/32	- 1/16							- 1/4	- 3/4
T-6	IV	60	18.8	5/8	1 3/4	Spalled on compr. face	+0.87	+0.11	+0.42	0.07	-0.10	4 1/8	8 7/8
	II	60	23.2	1/16	1/8							- 1/8	- 3/4
	I	30	19.7	±1/32	± 1/16							- 1/2	-1 3/8
	III	30	22.2	±1/16	± 1/8							- 3/8	-1 1/8
T-2	I	60	21.5	1/64	1/32		+0.38	-0.18	+0.62	0	-0.02	- 3/8	- 7/8
	III	60	25.6	1/64	1/32							- 3/8	- 7/8
	IV	30	22.2	-	-							- 1/8	- 3/8
	II	30	24.6	1/64	1/64							- 1/4	- 5/8
T-7	I	45	19.2	1/16	3/16		+0.28	-0.96	+0.47	+0.08	-0.07	- 1/4	- 7/8
	IV	45	19.2	1/16	3/16							- 1/4	- 3/4
	II	45	22.8	1/16	5/32							- 1/4	- 1/2
	III	45	22.8	1/16	1/8							- 1/2	-1
T-3	I	45	21.8	1/64	1/64		+0.47	0	+0.57	0	-0.01	- 1/4	- 5/8
	IV	45	21.8	1/64	1/32							- 5/8	-1
	II	45	25.3	1/64	1/32							- 1/2	-1 1/4
	III	45	25.3	1/64	1/64							- 1/4	- 1/2

TABLE III

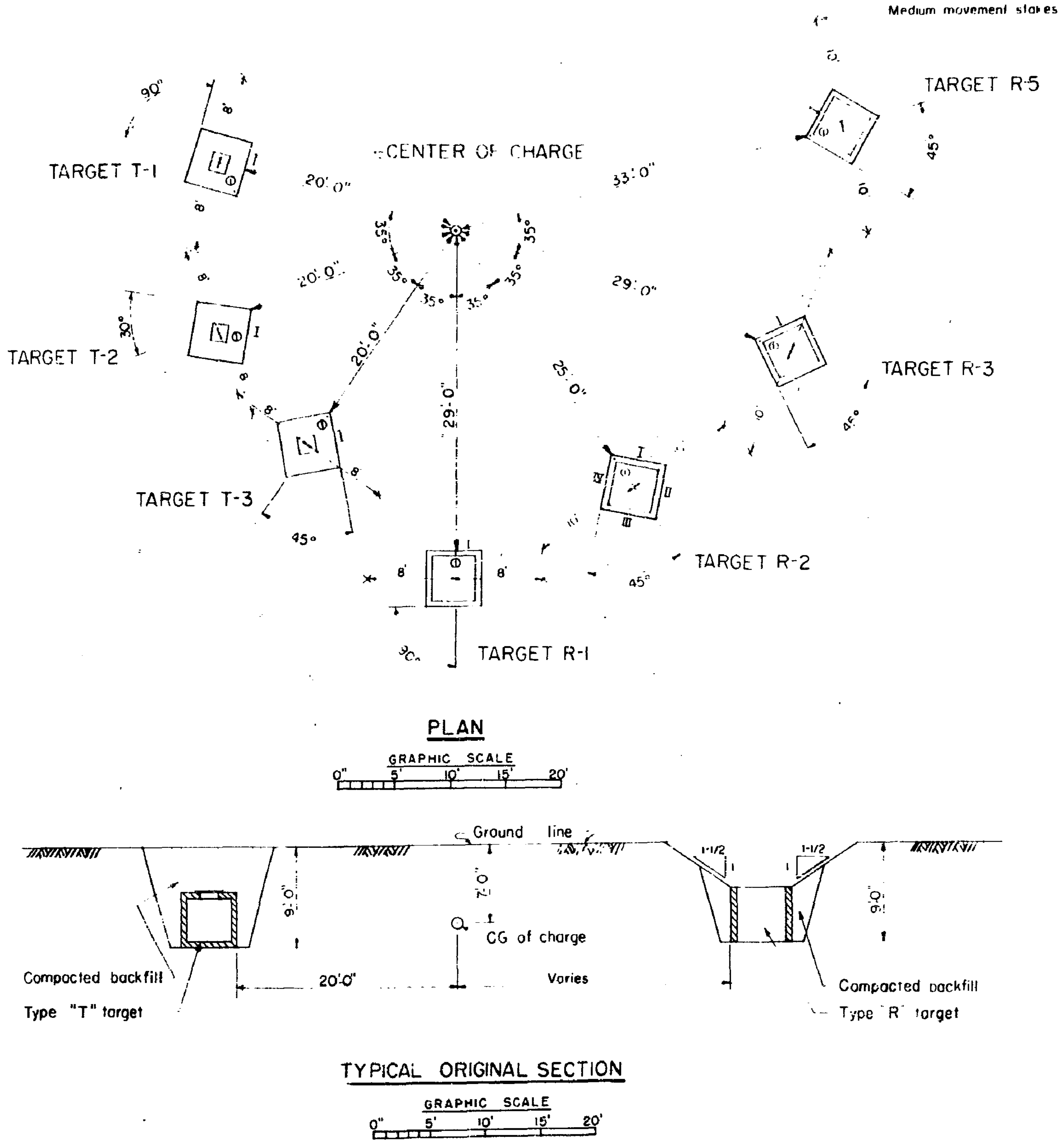
SUMMARY OF EFFECTS AT 20 FT. FROM CHARGE

Target and Inclination of near face	Maximum crack, inches	Summation of cracks inches	Maximum Deflection inches	Summation of Deflections inches
T-90	0.50 (1.00)	1.00 (1.00)	2.0 (1.00)	4.5 (1.00)
T-60	0.10 (0.20)	0.20 (0.20)	3.0 (1.50)	5.0 (1.11)
	*0.48 (0.96)	*1.08 (1.08)		
T-45	0.04 (0.08)	0.07 (0.07)	-	-
	**0.05 (0.10)	**0.13 (0.13)		
T-30	0.03 (0.06)	0.05 (0.05)	-	-
R-90	0.4 (1.00)	1.7 (1.00)	2.0 (1.00)	4.5 (1.00)
R-60	1.0 (2.50)	2.0 (1.17)	4.0 (2.00)	9.0 (2.00)
R-45	0.3 (0.75)	1.0 (0.58	1.5 (0.75)	3.0 (0.67)
R-30	-	-	-	-

Note:

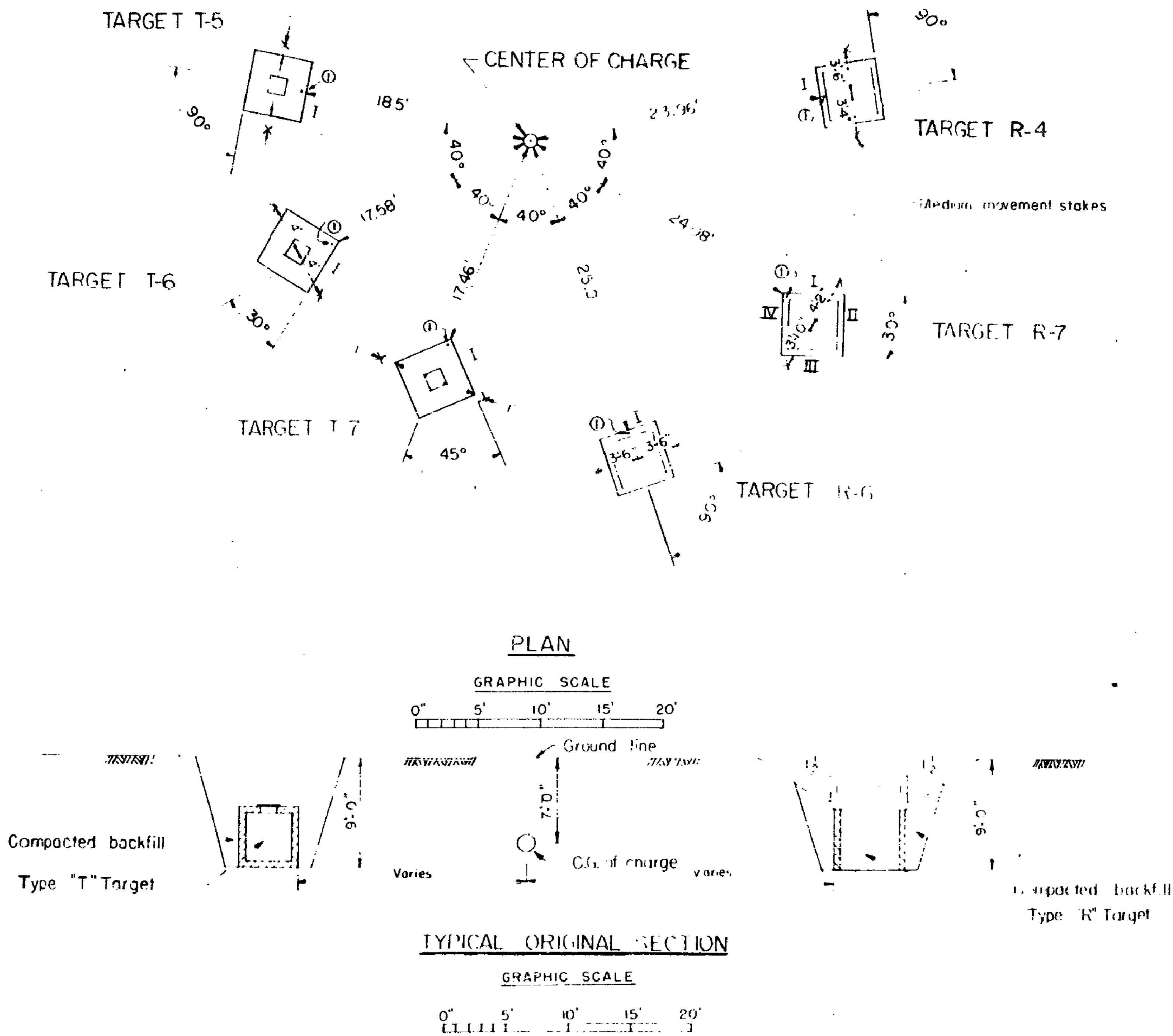
* These values obtained ignoring point T-2-60 in Figures 4 and 5.

** " " " " " T-3-45 " " " " ".



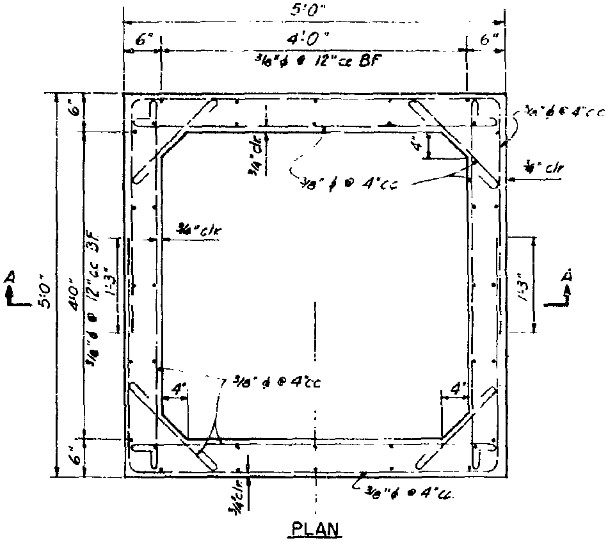
ROUND S-2-SUPPLEMENTARY SKEW STRUCTURES PROGRAM

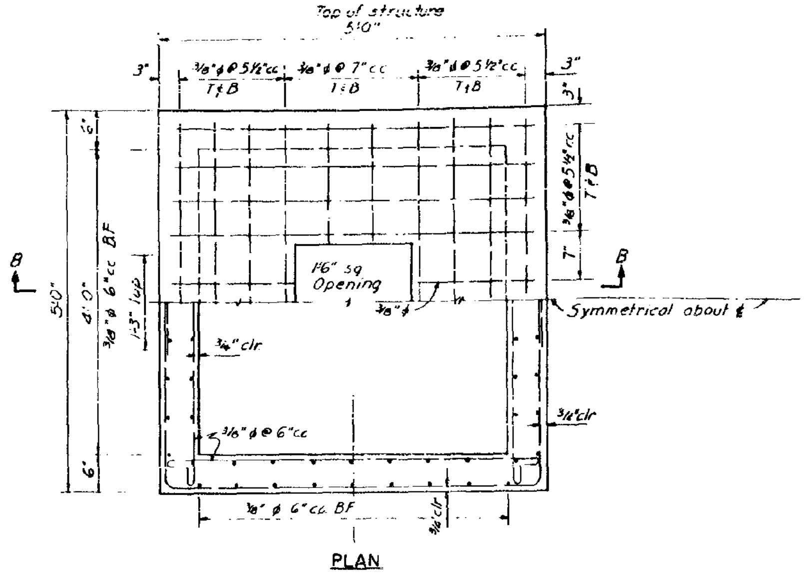
Figure 1

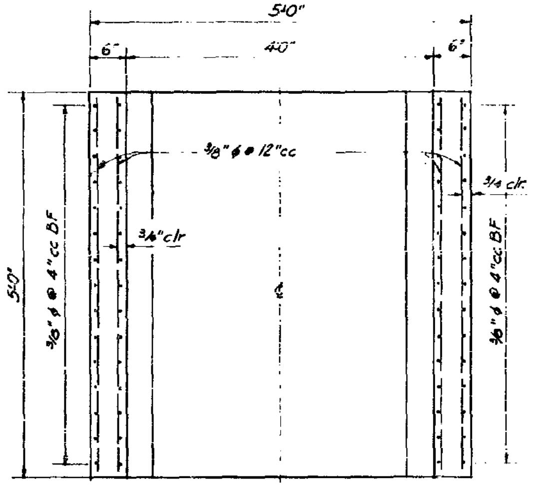


ROUND S-3- SUPPLEMENTARY SKEW STRUCTURES PROGRAM

Figure 2



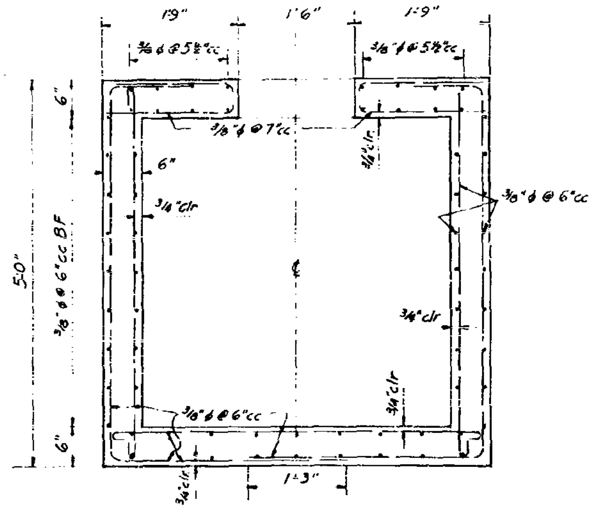




SECTION A-A

TARGET TYPE "R"

SCALE: 1"=1'-0"



SECTION B-B

TARGET TYPE "T"

SCALE: 1"=1'-0"

GRAPHIC SCALE

1"=1'-0" 0' 1' 2' 3'

TARGETS – PLANS AND SECTIONS

Figure 3

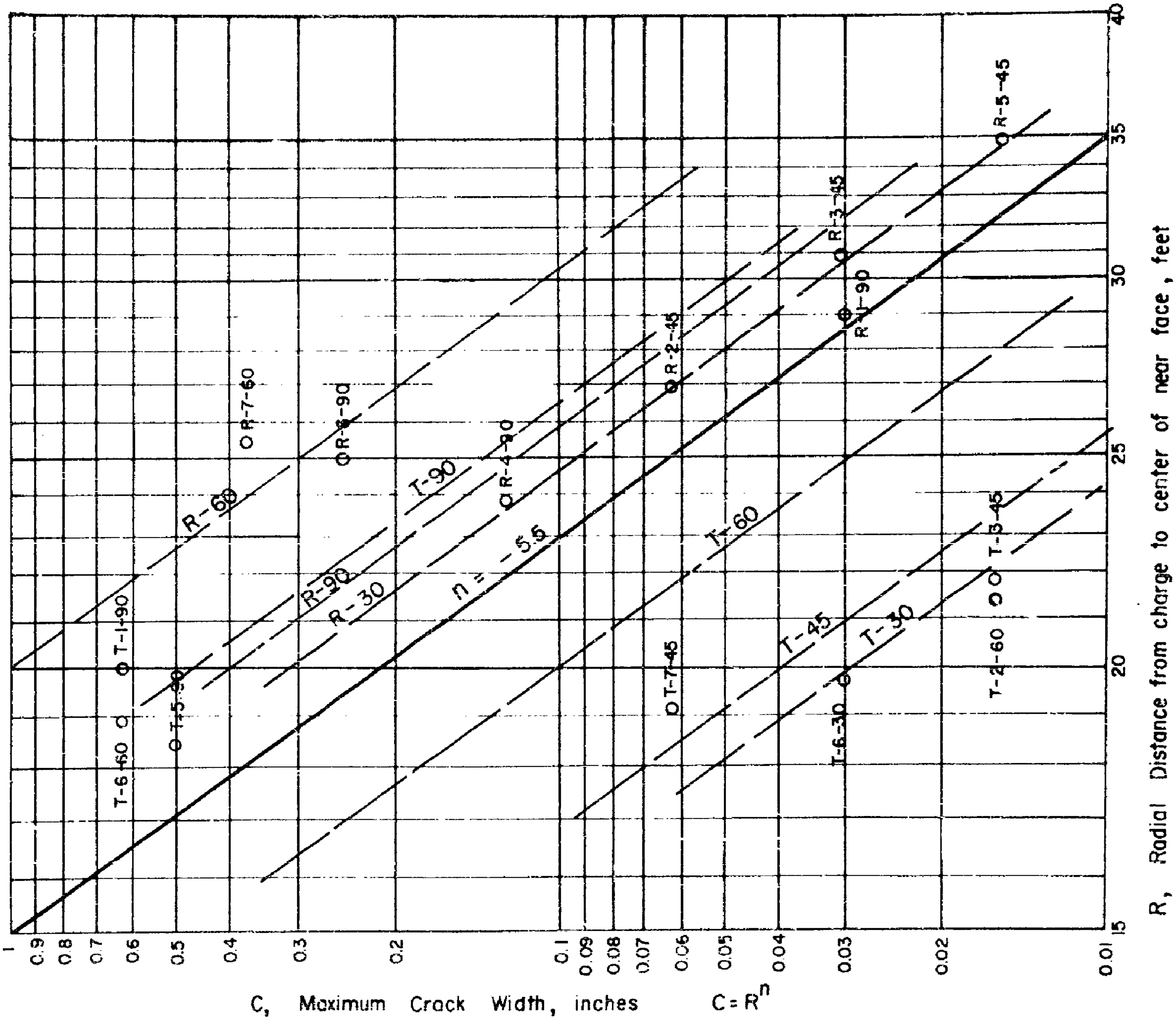

R, Radial Distance from charge to center of near face, feet
C, Maximum Crack Width, inches
$C = R^n$
n = −5.5
R-60
R-90
R-30
T-90
T-60
T-45
T-30
R-5-45
R-3-45
R-1-90
R-2-45
R-7-60
R-4-90
T-1-90
T-5-90
T-6-60
T-7-45
T-6-30
T-2-60
T-3-45

Figure 4

Note : ● represents 50% of T ; ○ represents 100% of T

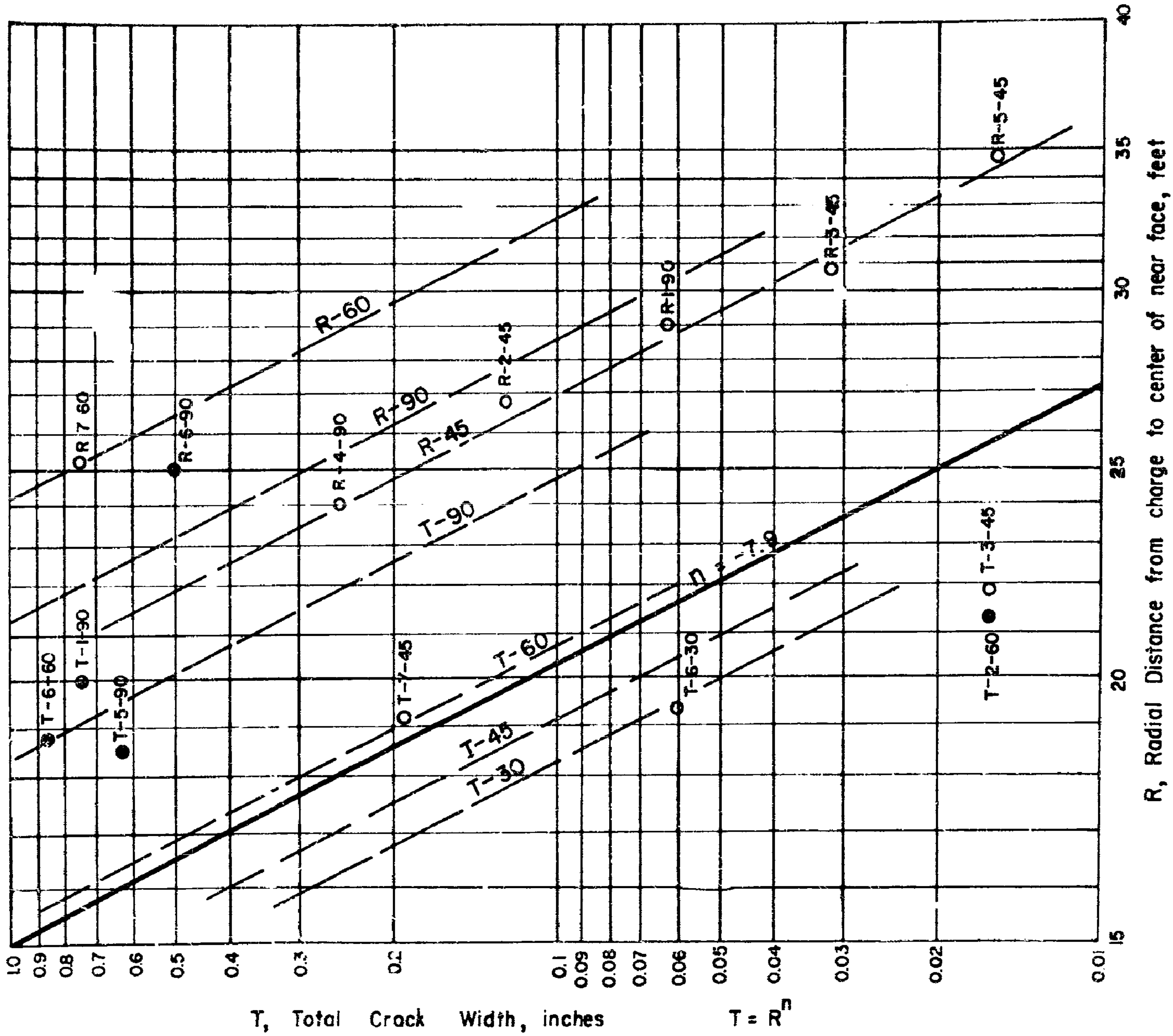


Figure 5

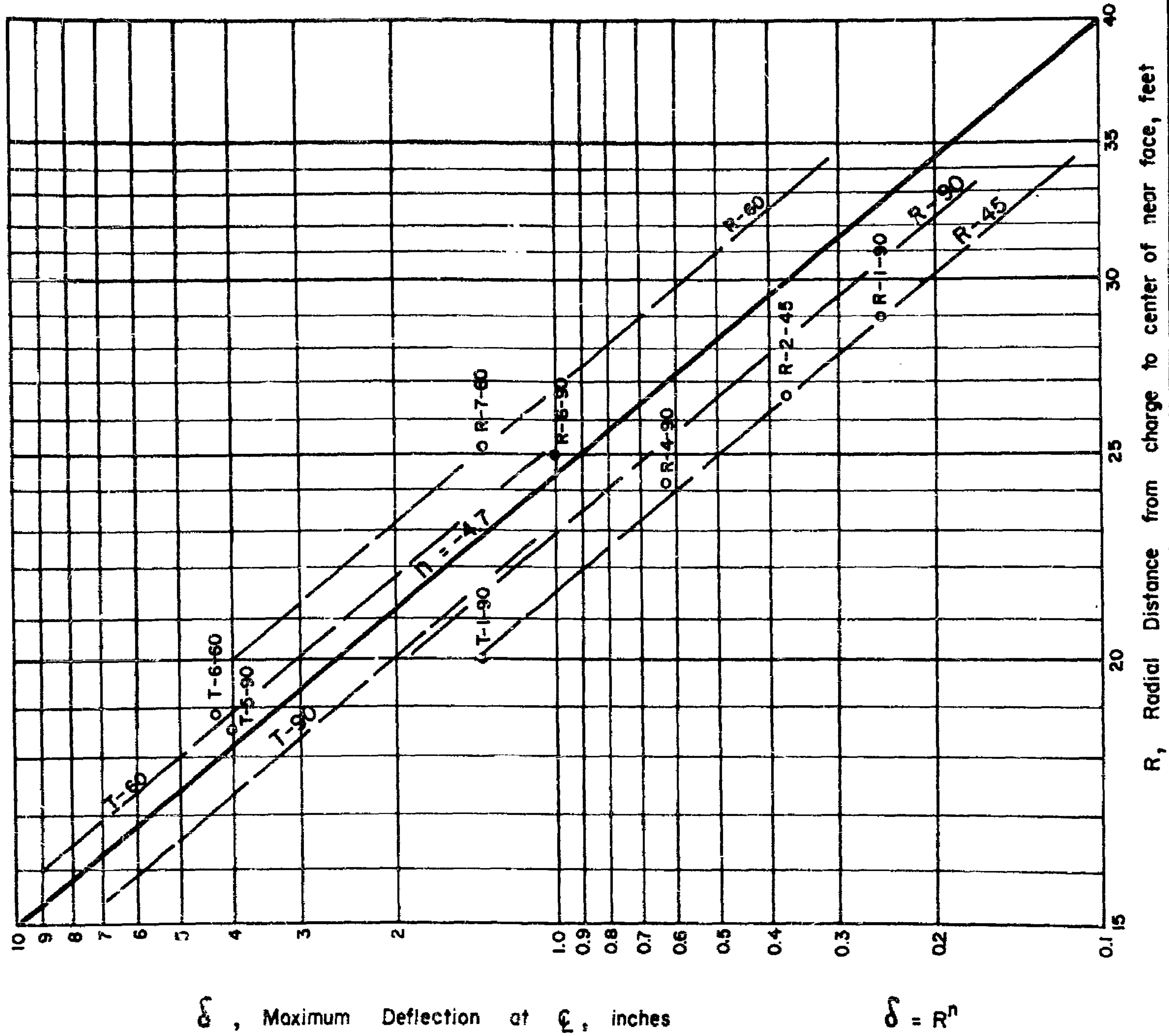
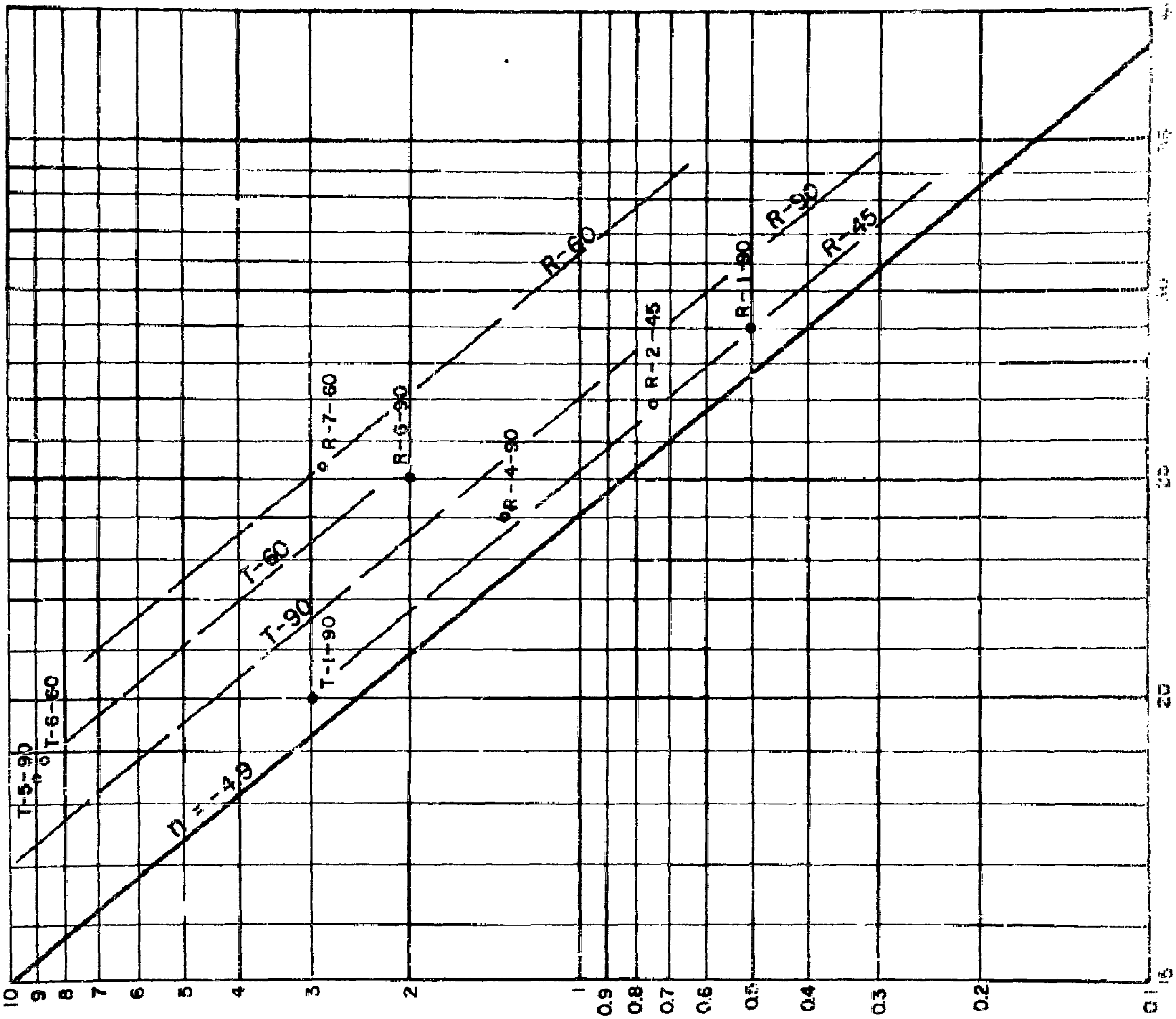

R-60
R-90
R-45
o R-1-90
o R-2-45
o R-7-60
R-5-90
o R-4-90
n = -.47
T-1-90
o T-6-60
o T-5-90
T-90
T-60
10
9
8
7
6
5
4
3
2
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
15
20
25
30
35
40
R, Radial Distance from charge to center of near face, feet
δ, Maximum Deflection at ℄, inches
δ = R^n

Figure 6



Δ, Sum of Deflections at C and quarter points, inches

$\Delta = R^{n}$

Figure 7

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